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## Kenaf productivity and morphology, when grown in Iowa and in Kentucky

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Marie Bourguignon, Kenneth Moore, Andrew Lenssen, Sotirios Archontoulis, Ben Goff, and Brian Baldwin

## **Kenaf productivity and morphology, when grown in Iowa and in Kentucky**

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## **Abstract**

Kenaf (*Hibiscus cannabinus* L.), mostly produced in China and India, is grown to a limited extent in the U.S., although this natural fiber can be a promising alternative to synthetic fibers for reinforcing plastic or other composite materials, or fuel purposes. Producing kenaf in the Midwestern U.S. could provide a local source of this fiber for use in a number of manufactured products and potentially for use as a biofuel feedstock. The objectives of this study were to: 1) compare the productivity and the morphology of kenaf cultivars 'Tainung 2' and 'Whitten' when grown in Iowa and Kentucky and harvested after the first killing frost; 2) assess kenaf growth over the growing season; and 3) determine management (variety and seed density) effects on kenaf productivity and morphology. In 2014 and 2015, varieties 'Tainung 2' and 'Whitten' were grown at 185300 and 370700 seed/ha in Iowa and in Kentucky. Stem and leaf biomass, plant population, core:bast ratio, stem height and diameter, leaf area index (LAI), and nitrogen concentration were measured during 6 in-season harvests and at the final harvest. Results showed that, 'Tainung 2' and 'Whitten' grown in Kentucky in 2014 yielded 24 and 19 Mg/ha, respectively, whereas both cultivars reached a final yield of 8 Mg/ha in Iowa. However, in 2015, final yields were similar for both locations (12.6 Mg/ha on average). It was found that variety and seed density treatment effects were starting to be observed during the growing season, and that, when grown in Iowa, kenaf response to treatments was less variable over time than in Kentucky. With respect to fiber production, growing 'Tainung 2' in Kentucky produced plants with 16% more core fiber than in Iowa, but using that same variety in Iowa would result in higher bast production. Therefore, a producer in Kentucky could influence kenaf productivity by changing management practices and variety. Overall, kenaf production is very feasible in Kentucky and Iowa, but Kentucky has greater yield potential.

## **Keywords:**

Kenaf fiber, Seed density, Nitrogen, Tainung 2, Whitten

## 1. Introduction

Replacing petroleum-based materials with renewable materials is of critical importance for the transition from a petroleum-based economy to a renewable bioeconomy. The use of natural fibers derived from plants is one way to address the economic and environmental problems associated with the use of synthetics. It is crucial to find an alternative to petroleum-based plastics and composites, since they account for the greatest volume of products made by humans and since they persist in the environment long after their useful life. An example of a plant grown for fibers is kenaf (*Hibiscus cannabinus* L.), an annual, non-food fiber crop originally from Africa (Cheng et al., 2004). Kenaf is an efficient lignocellulosic crop that can reach a height of 4 to 6m and can yield 24 Mg/ha in 5 to 7 months with low inputs (Brown and Brown, 2014).

The industrial attractiveness of kenaf lays in its anatomy. The kenaf stem is composed of an inner core (60-65% of kenaf stem volume) that contains short and porous fibers (0.6 mm-length and 33  $\mu\text{m}$ -width on average), which make it attractive for absorbent material applications and thermal insulant tiles (K.E.F.I., 2011; Monti and Alexopoulou, 2013; Zaveri, 2004). The outer bast (35-45% of kenaf stem) is composed of long fibers (2.5 mm-length and 17  $\mu\text{m}$ -width in average; Sellers and Reichert, 1999) that have been used in textile, paper pulp, and cordage industries (Bel-Berger et al., 1999). Other potential applications for bast and core are reinforcements in bioplastics and biocomposites, biofuel production, and other chemical end-use products (Aji et al., 2009; Inoue et al., 2007; Saba et al., 2015). Particularly, numerous studies have highlighted the competitiveness of kenaf bast fibers in the production of reinforced polymer products, using vacuum-assisted resin transfer molding (Xia et al., 2016a; Xia et al., 2015b). It has also been pointed that a kenaf fiber/polyester composites can replace glass fiber in the automotive industry, when impregnated and treated for water resistance, and that mechanical properties are often dramatically enhanced (Xia et al., 2015a; Xia et al., 2015c; Xia et al., 2016b).

Kenaf was introduced in the U.S. during World War II as a source of bast fiber to make cordage to help meet war-time demand (Dempsey, 1975). At the height of U.S. production, much research was done

on kenaf (Webber et al., 2002). There were approximately 10,000ha of land cultivated with kenaf in 2000, mostly located in Mississippi, New-Mexico, Georgia and Texas, Southern states in general and none in the Midwestern states.

Kenaf production in the U.S. is currently not able to compete economically with overseas production. Indeed, the total production of kenaf in the world was 352000 Mg in 2010/2011 and in 2015, India and China, respectively, produced 44% and 29% of world kenaf production (I.N.F.O., 2016). Kenaf has received a lot of attention in Asia because kenaf production has been present there for many years, but interest in the U.S. has been increased until recently. There has been recognition that there is a need to increase the use of biofibers and add crop diversity in the landscape to promote soil health. Additionally, growing kenaf in the U.S. could contribute to agriculture and bioindustry diversity.

Literature on kenaf growth and production in the U.S. Corn Belt is rare, however, kenaf could become well established as a specialty crop in the Midwest, especially in Iowa, if properly grown (Baldwin, 1996; Janick et al., 1996). Iowa crop production is mostly based on feed, food and fuel industries, but at this time, the fiber industry is not important. About 70% of Iowa's landscape is dominated with corn and soybean crops and several research studies have indicated the need to diversify crop rotations in Iowa (Davis et al., 2012; Karlen et al., 2006). Adding kenaf into existing crop systems in Iowa would move the economy of the state even further towards a bioeconomy. It has already been noted that kenaf is a good candidate for a biofuel feedstock (Berti et al., 2013; Meryemoğlu et al., 2014; Saba et al., 2015) and Iowa leads all other states in biofuel production. Also, research has shown that kenaf may be appropriate as a supplement feed crop (Webber et al., 2002), which could be attractive for livestock production.

In contrast to Iowa, Kentucky is a southern state and is generally warmer and wetter than Iowa, which allows Kentucky to have a longer growing season. Kenaf has been studied in the past in Kentucky (Clark et al., 1963; Toole et al., 1960), but Kentucky lost interest in this crop in the early 2000. Producers in Kentucky wish to grow more fiber crops and to diversify the landscape. In some ways, Iowa could be a good location for kenaf production because of its rich soil (plant available water content of about 250 mm

and soils with organic matter of 6%, latitude 42°N; SolarGIS, 2014) but Kentucky could be more favorable due to its climate (7% more annual radiation and 14% higher annual temperature than Iowa, latitude 38°N; Figure 1). Ultimately, the questions of what is more important for kenaf growth and productivity and how morphology and crop physiology change across these environments are raised. To answer these questions, a comparative growth analysis was performed between the two sites.

In this study, the goal was to investigate kenaf productivity, morphology, and physiology of two kenaf cultivars under two management practices in Iowa and in Kentucky. More specifically, the objectives of this study were to: 1) compare kenaf productivity between Iowa and Kentucky; 2) assess kenaf growth over the growing seasons; and 3) determine management (variety and seed density) effects on kenaf productivity, morphology, and physiology. In this work, it was expected to observe differences in kenaf productivity between Iowa and Kentucky, and a better performance under southern climates. Plant growth was hypothesized to have a different profile when grown in Iowa or in Kentucky. Finally, local management was expected to have different effects when kenaf is grown in Iowa or in Kentucky.

## **2. Material and Methods**

### *2.1. Site, experiment, and local climate*

The experiment was conducted at two diverse locations, the Iowa State University Agronomy and Agricultural Engineering Research Farm, near Boone, Iowa (42°01'N, 93°46'W) and at the University of Kentucky Spindletop Research Farm, in Lexington, Kentucky (38°10'N, 84°49'W). The Iowa site had a Nicollet loam soil (fine-loamy, mixed, mesic Aquic Hapludoll) and the Kentucky soil was a Bluegrass-Maury silt loam complex (well-drained, fine-silty, mixed, active, mesic Typic Paleudalf). The study was repeated at both sites in 2014 and 2015. At each site and in each year, the experiment was a randomized complete block design with three replications; each plot was 4.6 by 9.1 meters.

The cultivars 'Tainung 2', originally from Taiwan, and 'Whitten', developed at Mississippi State University (Baldwin, 2006) were planted and evaluated for phenology, crop biomass and morphology

characteristics in 2014 and in 2015. Those two varieties have presented promising results in terms of fiber yield (Bourguignon et al., 2016) and a good establishment in the field under Iowa environmental conditions. Kenaf seeds were planted at 185300 and 370700 seed/ha in rows spaced 38-cm apart at a depth of 2.5 cm when the top 10 cm soil temperature reached 15.6°C. Nitrogen was applied at a rate of 168 kg/ha N and weeds were controlled with Prowl H<sub>2</sub>O Herbicide (pendamethelin). In 2014, kenaf was seeded on 6 June in Kentucky and 10 June in Iowa. In 2015, kenaf was planted on 26 May in Kentucky and on 2 June in Iowa.

In order to assess kenaf growth over the season, destructive harvests were performed several times from after planting to after the first killing frost (-2°C) at each location. In 2014, both locations received 6 in-season harvests, starting two weeks after planting. But in 2015, only Iowa had 6 in-season harvests, whereas the plots in Kentucky, subjected to a severe attack of Japanese Beetles (*Popillia japonica*), allowed to only have 4 in-season harvests. A final harvest was done on two 2-meter rows at both locations in both years. All harvests per year and location are presented in Table 1.

The weather conditions of the Iowa and Kentucky sites were quite different in 2014 and 2015. Temperature and rainfall in Iowa for both years were similar to what the region was accustomed to in the spring and in the fall (Fig. 1). January and February were colder and drier than usual but, in November and December, were warmer and wetter, especially for 2015. The growing season (June to November-December) was slightly colder than average both years but the site received more rain than normal, especially in June and August.

Compared to Iowa, Kentucky weather was less extreme during 2014 and 2015. Indeed, the range of temperatures over both years was from -2°C to 25°C in Kentucky, whereas it was from -10°C to 25°C in Iowa. Also, Kentucky received in general more precipitation than Iowa. During the growing season, the Kentucky site was slightly warmer than the long-term period but it received more rain in June and July 2015. Thus, the two locations represented unique growing environments for comparing the growth and development of kenaf under similar management.



## *2.2. Data collection*

Prior to each harvest and at each location of this study, leaf area index (LAI) was measured with a LAI 2000 Plant Canopy Analyzer (PCA, Li-Cor, Lincoln, NE, USA) by taking one measurement above the canopy and three measurements below the canopy at ground level. Then, in order to evaluate plant population and kenaf yield, stalks were counted and wet aboveground biomass was recorded when two 1-meter rows were harvested by hand, cutting the plants at the ground-level.

Three representative individuals were taken from the harvested bulk to be evaluated for their morphology. Stem height and diameter, wet and dry weight of stem (bast and core when differentiated) and leaves were measured on them. A measuring tape was used from apex to ground level to measure the stalk height and a caliper placed at ground-level was used for the stem diameter. Each of the three stalks was peeled and separated into bast, core and leaves. Wet weight and dry weight were determined after samples were dried at 60°F until the moisture content stabilized. This step was used to assess the core:bast ratio (dry weight of core divided by dry weight of bast) and the leaf:stem ratio (dry weight of leaf divided by dry weight of stem). These characteristics were later used to compare performance among treatments (cultivar and seed density).

Nitrogen concentration was assessed in kenaf during the growing season. This analysis provides information regarding kenaf composition and forage quality. Dry leaves, core and bast of each harvest were ground at 1-mm sized using a Wiley Mill, homogenized and prepared for N analysis. A 3 to 5 mg sub-sample was mixed with tungsten trioxide and placed in Elemental Analyzer (Vario MICRO cube, Elementar) to determine the concentration of N. Acetanilide was used to make reference as standards in this procedure.

## *2.3. Statistical analysis and non-linear model*

The experiment was designed as a randomized complete block design with three replications. The statistical analyses were performed in SAS 9.4 using Proc GLM. Year and blocks were considered as random effects. A combined analysis was performed using location, variety, and seed density as fixed factors in the ANOVA for each year separately, but including only the final harvest in each model (main effects results presented in Table 2). Since the harvests were not conducted at the same time in Kentucky and in Iowa, the analysis of the location effect was only appropriate for the final harvest. An ANOVA was conducted separately for each location and each year, this time including harvest (represented by days after planting), variety, and seed density. The specific goal of this analysis was to address the cultivar and seed density effects over time. All statistical tests were made using  $\alpha = 0.05$  unless otherwise noted and only the significant results are presented in this study.

In this study, the beta growth function (Yin et al., 2003) was to fit total dry biomass, height, diameter, and LAI:

$$Y = Y_{max} \left( 1 + \frac{te - t}{te - tm} \right) \left( \frac{t}{te} \right)^{\frac{te}{te - tm}} \quad (1)$$

where Y is the total dry biomass (or LAI),  $Y_{max}$  is the maximum total dry biomass (or LAI) value, t is the time (day of year),  $t_e$  is the time when  $Y_{max}$  is reached,  $t_m$  is the inflection point at which the maximum growth (or LAI) rate is reached. This model was selected among many (Archontoulis and Miguez, 2015 for a review of 77 non-linear models), because it can describe decrease in biomass after a certon point. In the case of kenaf, total biomass increases with time, but after the first frost, all the leaves fall which results in an overall total biomass reduction. From the beta growth function (1) applied to total dry biomass, the maximum crop growth rate (CGR, kg/ha/d) was calculated (Yin et al., 2003):

$$CGR = \frac{2te - tm}{te(te - tm)} \left( \frac{tm}{te} \right)^{\frac{tm}{te - tm}} Y_{max} \quad (2)$$

Stem height and basal diameter were fitted using the weibull function (Weibull, 1951):

$$Y = Y_{asym} \left( 1 - e^{-at^b} \right) \quad (3)$$

where  $Y$  is the height (or diameter),  $Y_{\text{asym}}$  is the asymptotic height (or diameter) value,  $t$  is the time (day of year), and  $a$  and  $b$  are parameters determining the shape of the curve. This model was appropriate for height and diameter because, at the end of the vegetative growth, plants have reached their maximum height and diameter that do not decrease later. The software R was used to optimize the parameters  $Y_{\text{max}}$ ,  $t_e$ ,  $t_m$ ,  $a$ , and  $b$  in each case.

The software R was also used to compute the nitrogen dilution curve on N present in stem (bast and core). For this step, the following function was used, specific to C3 and C4 crops (Greenwood et al., 1990):

$$N = c * Y^d \quad (4)$$

where  $N$  is the N concentration (%),  $Y$  is the dry biomass (Mg/ha),  $c$  and  $d$  are parameters related the shape of the curve. As kenaf is a C3 crop, the optimized parameters were  $c = 5.7$  and  $d = -0.5$ . The N dilution in the stem (bast + core) were specifically presented, because the stem is the commercial product that most industries are interested on.

### 3. Results and Discussion

Biorenewable resources are very promising alternatives to petroleum for fiber and fuel. In this study, the growth of kenaf in Iowa and Kentucky was investigated and compared. Two years of data relevant to productivity and morphology of kenaf, cultivars ‘Tainung 2’ and ‘Whitten’, grown at two seed densities were analyzed. When all plant characteristics are compared, kenaf production in Iowa seems to be more stable over time than Kentucky and Iowa presented very few interactions between treatments. ‘Tainung 2’ was in general more sensitive to location and to management practices than ‘Whitten’. Looking at the development of kenaf over the growing season, kenaf plants started to rapidly grow at the end of July and kenaf growth slowed down in October until reaching a plateau due to low temperatures. Therefore, it appeared that harvesting the crop between 280 and 300 DOY would be best to obtain the highest yield. Also, depending on when a producer harvested the crop, management practices and variety can be of

importance. Finally, if a producer decides to grow kenaf for core, choosing ‘Tainung 2’ and growing it in the South, like Kentucky would be a good strategy. However, growing ‘Tainung 2’ in Iowa would produce more bast, which is generally a more valuable product.

### *3.1. Kenaf productivity and morphology in Iowa and in Kentucky when harvested after the first frost*

Kentucky, generally warmer and wetter than Iowa, usually has a longer growing season. Consequently, it was expected to observe differences in kenaf productivity between locations and a better performance under southern climates. This hypothesis was mostly confirmed, but not in both years. When the analysis of kenaf productivity was made on the last harvest of 2014 and 2015, the location in which kenaf was grown greatly affected stem height, core:bast ratio, and dry stem yield (Table 2; Fig. 1). Kenaf height in Iowa was 8% less than in Kentucky in 2014, however, this pattern was reversed in 2015, as kenaf was 32% taller in Iowa than in Kentucky. In 2015, kenaf in Kentucky was infested by Japanese beetles (*Popillia japonica* Newman) that damaged the leaves of many plants, reducing the ability of kenaf to grow due to the LAI reduction. In 2014, kenaf stem dry yield presented an interesting location × variety interaction, where ‘Tainung 2’ performed 25% better than ‘Whitten’ when grown in Kentucky, whereas both varieties produced a yield of 9 Mg/ha in Iowa ( $P = 0.0339$ ; Fig. 2-A). ‘Tainung 2’ and ‘Whitten’ have rarely been compared in previous studies, but results from Mississippi showed that these cultivars produced similar yield of 15.6 Mg/ha (Baldwin et al., 2006).

Location had no effect on kenaf yield in 2015 and this was probably due to the presence of Japanese Beetles in Kentucky. That year, kenaf in Iowa reached 35% higher stem height than kenaf in Kentucky while final harvest yields were similar at the end of the year (12.5 Mg/ha on average; Fig. 3). The pest damage resulted in a 43% yield reduction in Kentucky in 2015 compared with 2014. Because of the lower presence of pest and greater population variations under colder climates in some years, kenaf could perhaps experience less insect damage when grown in Iowa than in Kentucky. Kenaf production in Iowa seems to be more stable than Kentucky with respect of kenaf productivity.

No previous work has compared kenaf productivity in Iowa and in Kentucky and very few studies have investigated the location effect on kenaf performance. Ching et al. (1992) compared stalk yield, plant height, and stem diameter of kenaf grown in Missouri, Oklahoma, and Mississippi. The authors found that kenaf performed in general better when grown in Mississippi compared with the other locations. The farther north that kenaf was planted, the lower the stalk yield, suggesting that southern states were preferable for kenaf production. However, Ching et al. (1992) did observe varietal differences, including ‘Tainung 2’ reaching higher yield than other cultivars in all locations. This was not confirmed in this present study, because dry matter yield was dependent on variety and location (Fig. 2-A).

The core:bast ratio was also sensitive to both location and variety (Table 2; Fig. 2-B), confirming results of Ching et al. (1992). When kenaf was grown in 2014, contrary to height and yield, the core:bast ratio was 25% greater in Iowa than in Kentucky, which means that there was 25% more core produced than bast in Iowa but 25% more bast than core in Kentucky. Often, core:bast ratio parallels the stem diameter, however, in this case, no main effect of location was found on diameter in either of the two years (data not shown). In 2015, ‘Whitten’ produced the same core:bast ratio in both locations (approximately 1.8; Fig. 2-B), but ‘Tainung 2’ core:bast ratio was 14% higher when grown in Kentucky than in Iowa and was 10% lower than ‘Whitten’ when grown in Iowa. Based on these results, if a producer decided to grow kenaf for its core, choosing ‘Tainung 2’ and growing it in the South would be a good strategy, because the core:bast ratio is generally greater in Kentucky than in Iowa. However, growing ‘Tainung 2’ in Iowa would produce more bast, which is a more valuable product.

The interaction between variety and seed density also influenced final stem diameter and dry stem yield. In 2014, ‘Tainung 2’ plants had a 6% larger stem diameter than ‘Whitten’ when a low seed density was used (Fig. 2-C). Results showed that the more crowded the plants, the narrower the diameter of ‘Tainung 2’ stems, which was not the case for stems of ‘Whitten’. However, diameter was not affected by these treatments in 2015. That second year of study, the variety ‘Tainung 2’ was more sensitive to the seed density than ‘Whitten’ with respect to stem production, since ‘Tainung 2’ reached a 30% greater yield when the plants were 50% more crowded (higher seed density) than ‘Whitten’ (Fig. 2-D). Contrary

to what Ching et al. (1992) found, stem diameter was not influenced by location  $\times$  variety interaction. Overall, these results show that ‘Tainung 2’ was generally more sensitive to environment (represented by location here), as described earlier, and to management practices than ‘Whitten’.

### *3.2. Kenaf growth, morphology, and yield components during the growing season in Iowa and in Kentucky*

Seven in-season harvests were conducted in both locations in 2014, and seven in Iowa and four in Kentucky in 2015. In 2014, the first two harvests in Iowa and the first harvest in Kentucky were too early to observe bast and core differentiation, therefore, it was not possible to calculate the core:bast ratio. This also occurred with the first harvest at each location in 2015. Also, there were no leaves on the plants at the final harvest in 2014 and 2015 at each location, which prevented leaf area index measurements and calculation of the leaf:stem ratio.

For all variables measured, the harvest date had a significant effect. Fig.3 represents the kenaf growth (total dry yield, height, and diameter) for both locations in 2014 and in 2015, whereas Fig. 4 presents kenaf morphology (core:bast ratio, leaf:stem ratio, and LAI). It was hypothesized that the plant growth would have a different profile, when grown in the Midwest or in the Southern U.S. All productivity-related responses followed a similar pattern over the growing season in both years and locations. For instance, dry aboveground yield, stem height, and stem diameter increased with time, in a sigmoidal pattern. First, kenaf growth increased very slowly but, starting in July (180-200 DOY) when the monthly average temperature reached 20°C, the overall aboveground dry yield dramatically increased (2 to 19 Mg/ha on average in 100 days in 2014; Fig. 3-A; 5 to 17 Mg/ha on average in 100 days in 2015; Fig. 3-B), reflecting the fact that the plants grew taller and taller (50 to 250 cm in 100 days in 2014; Fig. 3-C; 100 to 250 cm on average in 2015; Fig. 3-D), and developed thick stem diameters (10 to 20 cm in 100 days in 2014 and 2015; Fig. 3-E, -F). However, in 2014, both locations experienced a slowdown in kenaf productivity at the end of August (200-240 DOY). In Iowa and Kentucky, and in both years, the non-

linear model parameter  $t_e$  was approximately 298 DOY, which means that no matter when it was planted and which climate it was in, kenaf maximum dry biomass was reached at the same time (15.8 and 23.1 Mg/ha in 2014 in Iowa and Kentucky, respectively; and 14.0 and 19.6 Mg/ha in 2015 Iowa and Kentucky, respectively; Table 3). But, compared with the harvest date, the maximum total dry yield, described previously, was reached earlier in Iowa (136 and 144 DAP in 2014 and 2015, respectively; Table 3) than in Kentucky in both years (142 and 152 DAP in 2014 and 2015, respectively; Table 3).

There were differences at some harvest dates between the two locations. Kenaf grown in Kentucky reached a greater yield than in Iowa, starting in September (from 30% at 245 DOY to 35% at 275 DOY; Figure 3-A), but in 2015, the difference in total dry biomass began before September and, after the killing frost, Kentucky and Iowa had similar yields (approximately 12 Mg/ha; Fig. 3-B). The non-linear model parameter  $Y_{max}$  indicates that in both years, Kentucky tended to have a higher maximum total dry biomass than Iowa (15.8 and 23.1 Mg/ha in 2014 in Iowa and Kentucky, respectively; and 14.0 and 19.6 Mg/ha in 2015 Iowa and Kentucky, respectively; Table 3). In 2014, kenaf maximum growth rate in Kentucky was 315.9 kg/ha/d, reached in 101 DAP, whereas it was 212.7 kg/ha/d, reached in 93.2 DAP in Iowa. In 2015 however, the CGR in Kentucky was 35% lower than in 2014 (Table 3). The Japanese beetle infestation happened in mid-July, but the consequences were visible only later (Figure 3-B), probably because the beetles feed mostly on the leaves (Hawley and Metzger, 1940).

With respect to stem height and diameter and based on the non-linear models developed in Iowa and Kentucky, there were some differences between locations starting at the end of July or in August (225 DOY). Contrary to 2014 (Fig. 3-C), 2015 stems were 30% taller in Iowa than in Kentucky starting in August (200 DOY, Fig. 3-D), but stem diameter remained similar (21.2 and 21.6 cm for Iowa and Kentucky, respectively; Fig. 3-F; Table 3). Generally, maximum basal diameter (20 and 21 cm at 250 DOY in 2014 and at 260 DOY in 2015; Fig. 3-E, -F) was reached earlier in the year than maximum total dry biomass (approximately 20 and 17 Mg/ha at 297-298 DOY in 2014 and in 2015; Table 3). In 2014, stem diameters were 25% greater in Iowa than in Kentucky but only in August (225-250 DOY; Figure 3-E). This demonstrates that the stem morphology of kenaf was not always the same and in this case, Iowa

displayed very tall but relatively thin stems in 2015. Observations in Kentucky fields showed that, contrary to Iowa, the stems were more ramified, which may reduce the ability to kenaf to resist lodging from wind prior to harvest.

Little is known about kenaf growth in the U.S., but several studies have been conducted in Greece and in Australia. For example, growth of ‘Tainung 2’ was relatively different in Kopais, Greece than what was found in this present study (Alexopoulou et al., 2000). In Greece, ‘Tainung 2’ grew in a linear way until reaching its peak of biomass and then decreased after leaves abscised. The maximum total dry matter was 22 Mg/ha and was reached at 285 DOY, which was slightly earlier than in Iowa and in Kentucky (Archontoulis et al., 2011). Compared to other energy crop species, kenaf reached its maximum total dry biomass later (297 DOY in Iowa and in Kentucky) than fiber and sweet sorghum (*Sorghum bicolor* Moench; 265 and 275 DOY, respectively, Archontoulis et al., 2011), later than maize (*Zea mays*; 250 DOY) grown in Mediterranean environment, and it was slightly later than *Miscanthus* (*Miscanthus × giganteus*; 280 DOY). Plant height profile in central Greece though was very similar to the results of this study (Danalatos and Archontoulis, 2010). Kenaf grown in Iowa in 2015 (309 cm; Table 3) was in the range of what was observed in Greece (from 300 to 370 cm). No similar research has been published using ‘Whitten’.

With regards to kenaf anatomy, core:bast ratio was very different from one year to the next. In 2014, Iowa had larger core:bast ratio than in Kentucky, especially before October (1.5 and 0.75 in Iowa and Kentucky, respectively; DOY 255; Fig. 4-A). But the trend was different in 2015, in which both locations displayed a core:bast ratio of almost 2.5 in July (185 DOY; Fig. 4-B). This would indicate that kenaf produced 2.5 times more core than bast during this period. Contrary to the core:bast ratio, the leaf:stem ratio was relatively the same for 2014 and 2015 (approximately from 1.5 to 0.3 in 2014, and from 2.0 to 0.3 in 2015; Fig. 4-C, -D), but slightly different between locations. Plants had two times more biomass in leaves than stems in Iowa in both years (leaf:stem ratio of 2.0 and 2.3 at the beginning of 2014 and 2015, respectively; Fig. 4-C, -D), whereas during the same time period kenaf in Kentucky had roughly 1.3 times more leaves than stems (leaf:stem ratio of 1.1 and 1.5 at the beginning of 2014 and 2015, respectively;



Fig. 4-C, -D). In both locations and years, peak leaf:stem occurred in July (DOY 180, 1.3 and 2.0 for Kentucky and Iowa in 2014, 1.5 and 2.3 for Kentucky and Iowa, in 2015), paralleling the fast vegetative growth, and reached a plateau where the leaf:stem ratio was 0.3. Total leaf biomass increased over the growing season, however, the stem weight became more and more important until the leaf:stem ratio was lower than 1. One might assume that the taller the plants, the more leaves they would have, but it was already demonstrated that stem height was not different in Iowa and in Kentucky in 2014.

As the leaf:stem ratio decreased in the summer, the leaf area index reached its peak in Iowa and in Kentucky in September 2014 (LAI of 4 in both locations; Fig. 4-E), when the plants were the tallest (about 250 cm; Fig. 3-C), and had the most leaves (leaf:stem ratio of 0.3; Fig. 4-E). In comparison, kenaf grown in Greece had a similar LAI trend, a parabolic profile, depending on the years (Archontoulis et al., 2011; Danalatos and Archontoulis, 2010). In 2015, the greatest LAI was achieved in Iowa earlier than in 2014 (3.9 at 245 DOY in 2014; 4.5 at 225 DOY in 2015; Table 4), and LAI in Kentucky was very low in 2015, likely due to the Japanese beetles that fed mostly on the leaves (LAI of 2.1, Table 4). Some studies have observed varietal differences in LAI (Alexopoulou et al., 2000), which was surprisingly not the case in this present study. Compared to other energy crop species, kenaf grown in Iowa and in Kentucky presented similar LAI than sunflower (*Helianthus annuus*; maximum LAI of 4) or maize (maximum LAI of 4; Archontoulis et al., 2011).

Despite differences in leaf morphology (divided and deeply lobed for ‘Tainung 2’ vs cordate and shallowly lobed for ‘Whitten’), LAI was influenced by irrigation in dry areas (Patanè and Cosentino, 2013), more than by variety. When precipitation patterns in Kentucky and Iowa were compared, Kentucky received less rainfall than in Iowa in the summer 2014 (approximately 160 and 110 mm in June and July in 2014, in Iowa and Kentucky, respectively; Fig. 1), but the trend was the opposite in 2015 (approximately 170 and 190 mm in June and July in 2015, in Iowa and Kentucky, respectively; Fig. 1). Even though Iowa received a similar amount of water in 2014 and 2015, Kentucky was much 30% wetter in 2015 than in 2014. Therefore, it was somewhat logical to have a lower LAI in Kentucky in 2015 than in 2014, whereas the LAI in Iowa was similar both years.

Nitrogen concentration in leaves, bast, and core, was the highest in the summer (180-210 DOY; Fig. 5-A, -B, -C, and -D), especially in Iowa and in 2015 (about + 67%; Fig. 5-B). Later, it slowly decreased over time as the stem and the leaves became older. Leaves averaged about 60% more N than the bast and the core. The pattern over time was very similar to that reported by Kipriotis et al. (2007), who found that N concentration in leaves and stem decreased with time. However, it was found that leaves contained between 35 and 50 g/kg N and that the stem had between 5 and 15 g/kg N. On average, this study showed that both leaves and stem were slightly richer in N than in their study (from 5 to 60 g/kg N; Fig. 5).

Kipriotis et al. (2007) used N fertilization rates of 60 and 120 kg/ha N, lower than 168 kg/ha N, applied in Iowa and in Kentucky. As kenaf grown in Iowa and in Kentucky received more N (168 kg/ha N), it seems logical that the N content of the samples was slightly higher than those grown in Greece. After applying 135 kg/ha N fertilizer, Iowan soils have 1.65 g/kg of total nitrogen, which mostly comes from nitrogen fertilization and soil organic matter (Brown et al., 2014). Considering the rich amount of soil organic matter in Iowa, compared with soil in Kentucky and in Greece, one could expect to have higher N concentration in kenaf grown in Iowa.

Data frequently collected of tissue dry biomass and N concentration allowed to build an N dilution curve, presented on Fig. 6. Similarly to other crops, kenaf N concentration decreases very rapidly when the dry weight increases, showing the dilution of N in the stem. Compared to Fig. 2 in Cassman et al. (2002), kenaf N dilution curve has a similar profile typical of C3 crops. However, the “elbow” of the curve is reached at 3% N and 2 Mg/ha, whereas other C3 crops present a “turn” at 2.5% N and 5 Mg/ha. Kenaf N dilution seems to be more in between C3 and C4 N dilution curves.

### *3.3. Seeding rate and variety effects on kenaf growth, morphology, and physiology during the growing season in Iowa and in Kentucky*

Variety and seed densities were the two agronomic factors used in this study. The third hypothesis, which stated that kenaf growth in Iowa and in Kentucky would be influenced by the variety and the seed

density was partially confirmed, mostly when kenaf was grown in Kentucky in 2014. However, the interactions between harvest date, variety, and seed density were not significant for any of the measurements performed in Iowa in 2014.

In Kentucky in 2014, the variety ‘Tainung 2’ planted at low seed density had one of the greatest total dry biomass in September (Trt 1, 10 Mg/ha, 245 DOY; Fig. 7-A), but not at the final harvest (Trt 1, 25 Mg/ha at 310 DOY; Fig. 7-A). However, when ‘Tainung 2’ was grown at high seed density, aboveground total biomass reached its peak in October (Trt 2, 31.8 Mg/ha, 264 DOY; Table 4). Maximum crop growth rate was observed when ‘Tainung 2’ was planted at 370660 seed/ha (31.8 Mg/ha; Table 4). ‘Whitten’ planted at low seed density (Trt 3, 17 Mg/ha; Fig. 7-A) was less productive than ‘Tainung 2’ at low density in October 2014 (275 DOY, Trt 1, 22 Mg/ha; Fig. 7-A). Surprisingly, the maximum crop growth rate for ‘Whitten’ was 49% greater when planted at 185330 seed/ha than at 370660 seed/ha, due to competition between plants during the period of maximum growth (Table 4). The core:bast ratio and the N concentration showed less differences between treatments over the year (Fig. 7-B, -C). However, ‘Whitten’ grown at high seed density had more core than bast in October 2014 (Trt 4, core:bast ratio of 1.3, 275 DOY; Fig. 7-B) and lower N concentration in August 2015 (Trt 4, 15 g/kg N, 215 DOY; Fig. 7-C) than for the other treatments (core:bast ratio of 1.0; Fig. 7-B, from 17 to 22 g/kg N; Fig. 7-C). This documents that, depending on when a producer harvests the crop, management practices and variety influence kenaf yield and quality.

Kenaf morphology, stem height, diameter, and leaf:stem ratio, was more sensitive to the influence of variety than to management practices in this study when grown in Kentucky in 2014 (Fig. 8). For instance, ‘Tainung 2’ was generally 12% taller and with 14% thicker stems than ‘Whitten’ starting relatively early in July and these differences slightly increased over the rest of the growing season (250 DOY; Fig. 8-A; Table 4). ‘Tainung 2’ had more leaf mass than stem mass (leaf:stem ratio of 1.3 at 175 DOY; Fig. 8-B) than ‘Whitten’ earlier in the season (leaf:stem ratio of 1.0 at 175 DOY; Fig. 8-B). Even though height, stem diameter, and leaf:stem partitioning were not influenced by seed density during the

growing season, the seed density treatment still impacted the aboveground kenaf yield, as previously described (Fig. 7-A).

Stem diameter and core:bast ratio were reported to be relatively highly correlated ( $r^2=0.39$ ; Webber, 1993), but in this present study, it was found that this was not the case because the coefficient correlation was not significant ( $r = -0.043$ ,  $p = 0.4993$ ; Table 5). ‘Tainung 2’ had 14% larger diameter than ‘Whitten’ (Fig. 8-A), but the core:bast ratio was not always greater for ‘Tainung 2’ (no significant varietal effect; Table 2). In general, ‘Tainung 2’ basal diameter over the season was relatively similar in Kentucky when compared with South Italy (from 5 to 25 in Iowa and Kentucky, and from 6 to 18 mm; Patanè and Cosentino, 2013). Specifically, kenaf grown in the Mediterranean area reached 18 mm-stem diameter whereas plants grown in Kentucky had a final diameter of 20 mm. Stem diameter was larger in Kentucky in 2015 when planted at 185330 seed/ha (25 mm) than when planted at 370660 seed/ha (18 mm) and the effects were visible in September (250 DOY; Fig. 9-A).

In contrast to Kentucky, kenaf growth and development was more stable over time with very few interactions between treatments. The core:bast ratio and N concentration of leaf and stem were the only variables that were influenced by the variety  $\times$  seed density interaction, and only in 2015 (Fig. 9-B, -C, -D). During summer 2015, the core concentration was higher than of bast when plants were planted at high seed density as the core:bast ratio were 1.9 and 2.7 for low and high density, respectively (180-250 DOY; Fig. 9-B). Moreover, the pattern was similar for core:bast ratio when the variety effect was studied, because ‘Whitten’ produced more core than ‘Tainung 2’ (from +37% to +5% from 185 DOY to 325 DOY, Fig. 9-C). ‘Whitten’ produced greater concentration of core than of bast, especially in early summer (+37%), but contained 22% less N than ‘Tainung 2’ during the same period (Fig. 9-D). Growing ‘Whitten’, especially at high seed density, reduced in general bast production and N concentration in the plant. Importantly, it should be noted that the differences discussed here were found during summer growth periods and differences in core:bast and plant N concentration were not present at the final harvest (Table 2).

Berti et al. (2013) was the only other group of who have recently investigated kenaf productivity in the Midwest, more specifically in North Dakota. The authors utilized the cultivar ‘Dowling’ and did not investigate a varietal effect but did find that yield was greater (9.45 to 10.22 Mg/ha, respectively) when the plants were planted at 160000 to 320000 plants/ha than when grown at 40000 to 80000 plants/ha. The seed density treatments used in Iowa and in Kentucky were in the range of what Berti et al. (2013) considered high plant densities and the yields were similar or slightly higher (8.21 Mg/ha in Iowa in 2014, and 12.61 Mg/ha in both locations in 2015). Based on these results, Iowa kenaf productivity and morphology may have varied among years, but ‘Whitten’ and ‘Tainung 2’ grown at 185330 or at 370660 seed/ha did not differ in yield, but only in distinct core:bast ratio and N concentration. This provides an opportunity for Iowan producers to choose variety and management practices depending on whether the purpose is to grow kenaf for bast or core. Kenaf yield in Kentucky averaged 21.6 Mg/ha, roughly double what Berti et al. (2013) reported from North Dakota, a region with less precipitation and a shorter growing season. Also, results showed that Kentucky produced on average 5.5 Mg/ha of core and 5.0 Mg/ha of bast over 2014 and 2015, whereas Iowa produced 4.1 Mg/ha of core and 3.0 Mg/ha of bast (data not shown, calculated from stem yield and core:bast ratio). This disparity provides evidence that Kentucky should have more potential for kenaf stem production than Iowa. Overall, the selection of variety and seed density decided at the planting season influenced kenaf growth in Iowa and in Kentucky. However, Iowa seemed much less sensitive than Kentucky to the treatments.

#### **4. Conclusions**

This study is one of the first to compare growth, morphology, production, and quality of kenaf between Midwest and a Southern state. Clearly, growing kenaf in Iowa has some advantages, especially in terms of stability for biomass production over varieties and seed densities. But Kentucky showed great potential to grow kenaf at high biomass. In general, ‘Tainung 2’ planted at high seed density will likely have greater yield at a late fall, penultimate harvest. A producer may choose to grow ‘Tainung 2’ in southern states to reach a high yield but, at the end of the growing season, the bast proportion may be

lower than when grown in the Midwest. Even though variety and seed density influence kenaf productivity and morphology during the growing season, the effects are not always apparent at final harvest. Therefore, it would be suggested to harvest kenaf between 280 and 300 DOY in both locations, considering the multiple factors that influence kenaf productivity and morphology.

This study focused on the influences of kenaf variety and seed density. Further research is necessary to optimize row spacing, nitrogen fertilization, and planting date for kenaf in the Midwest and Southern US. Bast and core proportion has been measured, but not the kenaf lignocellulose and ash content, which could be important for biofuel purposes. Kenaf has potential in Iowa, but it needs to be explored more thoroughly, especially as Iowa is one of the leading agricultural states of the U.S. Iowa would be the ideal location for kenaf production and processing, considering the farm acreage and the potential for developing bio-industries. This would give an opportunity for U.S. producers to compete with producers in Asia and India in the bio-fiber market.

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**Table 1**

Planting date, in-season and end-of-season harvests of kenaf grown in Iowa and in Kentucky, 2014 and in 2015.

Growing year	2014				2015			
Location	Iowa Date	DOY <sup>a</sup>	Kentucky Date	DOY	Iowa Date	DOY	Kentucky Date	DOY
Planting Date	10 June	161	6 June	157	2 June	153	26 May	146
Harvest	7 July	188	1 July	182	30 June	181	26 June	177
	21 July	204	18 July	199	14 July	195		
	4 August	216	8 August	220	31 July	212	27 July	208
	18 August	230	August 25 <sup>th</sup>	237	11 August	223		
	1 September	244	15 September	244	25 August	237	1 September	244
	15 September	258	8 October	281	17 September	260	9 October	279
	10 November	316	7 November	311	20 November	324	4 December	338

DOY = Days of year

<sup>a</sup> To calculate Day After Planting, use the planting dates, which were 161, 157, 153, and 146 DOY for Iowa and Kentucky in 2014, and Iowa and Kentucky in 2015, respectively.

**Table 2**

Location, variety, and fiber category main effects on kenaf height, core:bast ratio, and N concentration (mean  $\pm$  standard error; crop age 155, 154, 171, and 192 DAP for Iowa and Kentucky in 2014 and for Iowa and Kentucky in 2015, respectively).

	Stem Height		Core:Bast Ratio		N Concentration	
	cm				g/kg DM	
Year	2014	2015	2014	2015	2014	2015
Location						
IA	224 $\pm$ 4 b <sup>a</sup>	314 $\pm$ 5 a	1.2 $\pm$ 0.1 a	1.8 $\pm$ 0.1 a	10.0 $\pm$ 0.5 b	8.6 $\pm$ 0.4 a
KY	244 $\pm$ 6 a	214 $\pm$ 6 a	0.9 $\pm$ 0.1 b	1.9 $\pm$ 0.4 a	13.4 $\pm$ 0.8 a	8.5 $\pm$ 1.0 a
Variety						
Tainung 2	244 $\pm$ 6 a	276 $\pm$ 14 a	NS <sup>b</sup>	NS	NS	NS
Whitten	224 $\pm$ 5 b	262 $\pm$ 15 b	NS	NS	NS	NS
Fiber category						
Bast	NS	NS	NS	NS	13.5 $\pm$ 0.6 a	10.9 $\pm$ 0.6 a
Core	NS	NS	NS	NS	9.9 $\pm$ 0.7 b	6.2 $\pm$ 0.6 b

<sup>a</sup> Different letters (a, b) denote statistically significant differences of stem height, core:bast ratio, or N concentration between Iowa and Kentucky, between 'Tainung 2' and 'Whitten', or between bast and core (ANOVA,  $P = 0.05$ ), in each year.

<sup>b</sup> NS indicates  $p > 0.05$ .

**Table 3**

Parameters of non-linear model used to fit total dry biomass, stem height, basal diameter, and LAI for Iowa and Kentucky, in 2014 and 2015.

Year	Location	Total Dry Biomass <sup>a</sup>				Height <sup>b</sup>			Diameter <sup>b</sup>			LAI <sup>a</sup>		
		Y <sub>max</sub>	t <sub>e</sub>	t <sub>m</sub>	CGR	Y <sub>asym</sub>	a	b	Y <sub>asym</sub>	a	b	Y <sub>max</sub>	t <sub>e</sub>	t <sub>m</sub>
		Mg/ha	DOY <sup>c</sup>	DOY <sup>c</sup>	kg/ha/d	cm			cm			Mg/ha	DOY <sup>c</sup>	DOY <sup>c</sup>
2014	Iowa	15.8	297	254	212.7	216.2	0.000003	3.0662	20.2	0.000443	3.1830	3.9	245	220
	Kentucky	23.1	299	258	315.9	254.3	0.000084	2.1114	19.9	0.001015	1.6896	3.6	243	172
2015	Iowa	14.0	297	227	147.2	309.6	0.000031	2.4194	21.2	0.000004	1.9005	4.5	225	204
	Kentucky	19.6	298	234	205.9	224.7	0.000120	2.0654	21.6	0.002851	1.3471	2.1	258	185

Ymax = Maximum total dry biomass (or LAI) value

te = Time when Ymax is reached

tm = Inflection point at which the growth rate is maximized

CGR = Maximum crop growth rate

Yasym = Asymptotic height (or diameter) value

a and b = Parameters determining the shape of the curve

DOY = day of year

<sup>a</sup> The non-linear model used to fit the total dry biomass and LAI data was the Beta model.

<sup>b</sup> The non-linear model used to fit the stem height and basal diameter data was the Weibull model.

<sup>c</sup> To calculate Day After Planting, use the planting dates, which were 161, 157, 153, and 146 DOY for Iowa and Kentucky in 2014, and Iowa and Kentucky in 2015, respectively.

**Table 4**

Parameters of non-linear model used to fit total dry biomass, stem height, and basal diameter for Kentucky, in 2014.

		Total Dry Biomass <sup>a</sup>				Height <sup>b</sup>			Diameter <sup>b</sup>		
		Y <sub>max</sub>	t <sub>e</sub>	t <sub>m</sub>	CGR	Y <sub>asym</sub>	a	b	Y <sub>asym</sub>	a	b
		Mg/ha	DOY <sub>c</sub>	DOY <sub>c</sub>	kg/ha/d	cm			cm		
Variety	Seed density										
Tainung 2	185330 seed/ha	24.8	287	257	416.3						
	370660 seed/ha	31.8	295	264	515.7	269.9	0.0001	2.0550	22.0	0.0009	1.6890
Whitten	185330 seed/ha	23.2	292	269	412.4						
	370660 seed/ha	20.0	310	245	211.6	238.9	0.0001	2.1810	17.9	0.0012	1.6751

Ymax = Maximum total dry biomass (or LAI) value

t<sub>e</sub> = Time when Ymax is reached

t<sub>m</sub> = Inflection point at which the growth rate is maximized

Yasym = Asymptotic height (or diameter) value

a and b = Parameters determining the shape of the curve

CGR = Maximum crop growth rate

DOY = day of year

<sup>a</sup> The non-linear model used to fit the total dry biomass data was the Beta model. Total dry biomass was sensitive to variety and seed density (see Fig. 7).

<sup>b</sup> The non-linear model used to fit the stem height and basal diameter data was the Weibull model. Stem height and basal diameter were sensitive to variety only (see Fig. 8).

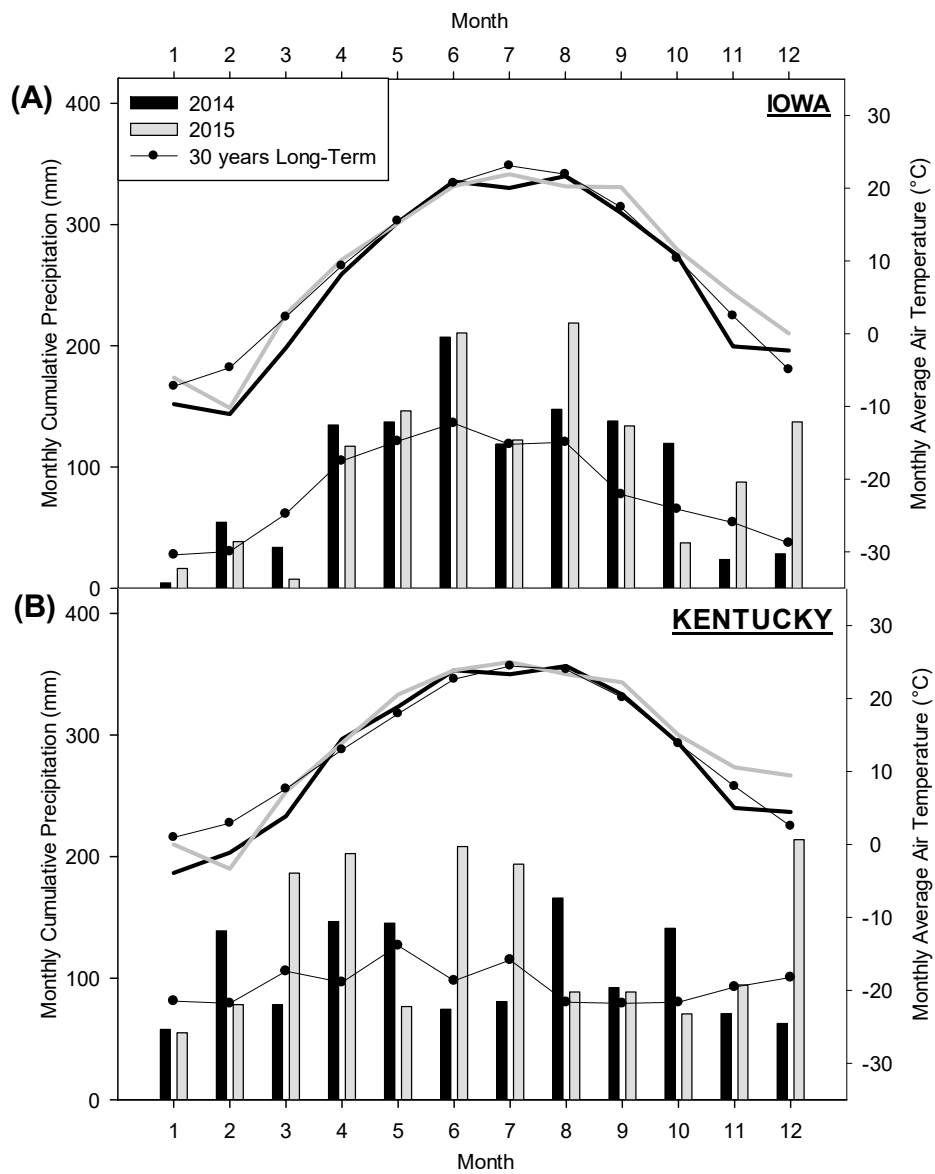
<sup>c</sup> To calculate Day After Planting, use the planting date, which was 157 DOY for Kentucky in 2014.

**Table 5**

Correlation coefficient of measured variables of kenaf grown in Kentucky and Iowa, in 2014 and 2015  
(all crop ages confounded).

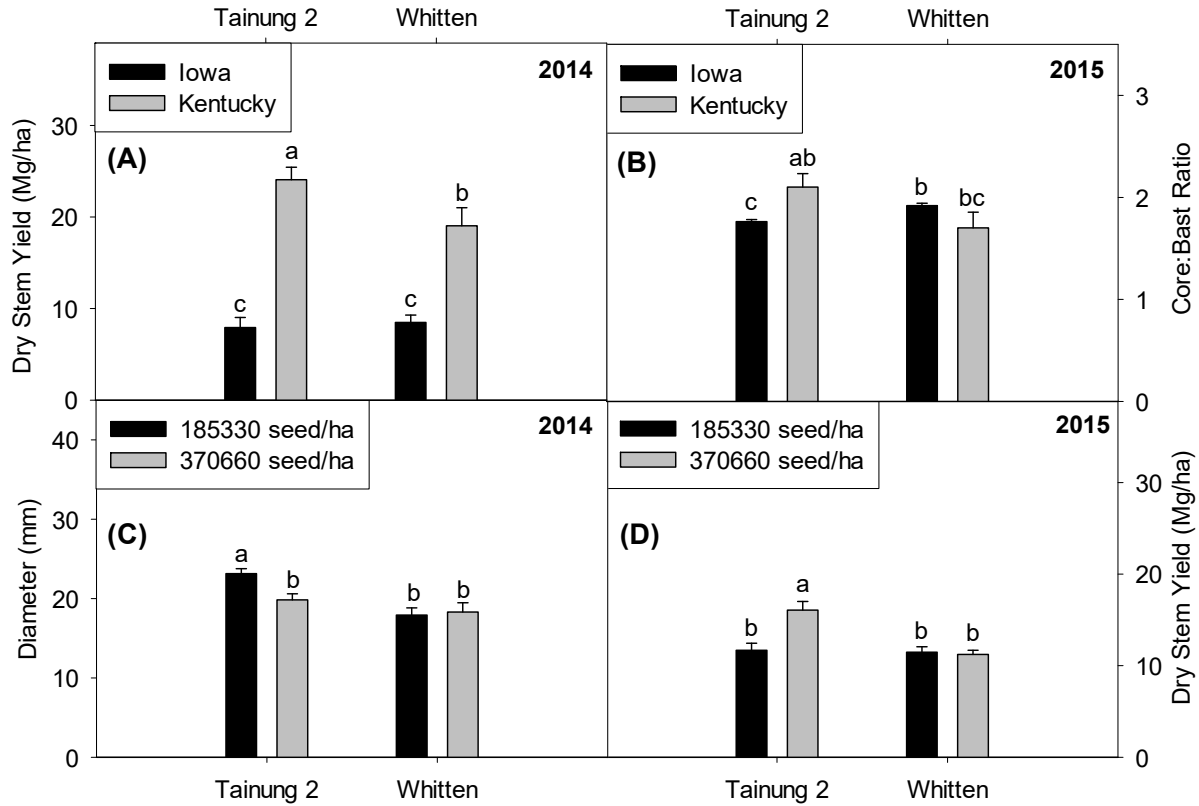
	Total Dry Stem	Leaf:stem ratio	Core:bast ratio	Height	Diameter	LAI
Total dry biomass	0.774 **	-0.529 **	-0.148 *	0.639 **	0.551 **	0.023 NS
Total Dry Stem		-0.459 **	-0.060 NS	0.676 **	0.745 **	-0.066 NS
Leaf:stem ratio			-0.078 NS	-0.865 **	-0.673 **	-0.301 *
Core:bast ratio				0.064 NS	-0.043 NS	-0.222 *
Height					0.758 **	0.369 **
Diameter						0.313 **

\*\*, \* Significant at the 0.001 and 0.01 levels of probability, respectively. NS = not significant ( $P > 0.05$ ).

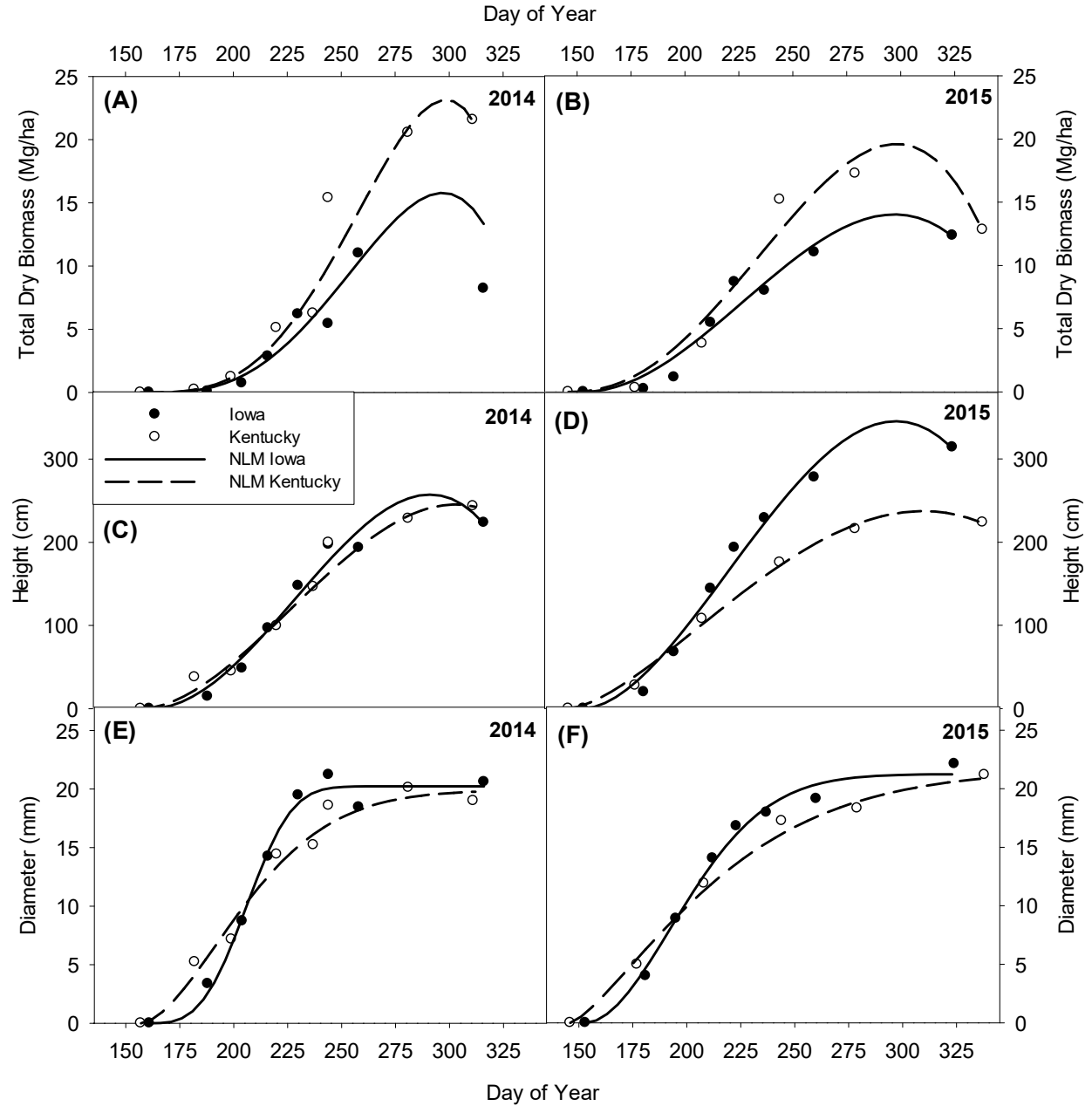


**Fig. 1.** Monthly cumulative precipitation and average air temperature in 2014 and 2015, in Iowa (A), and in Kentucky (B).

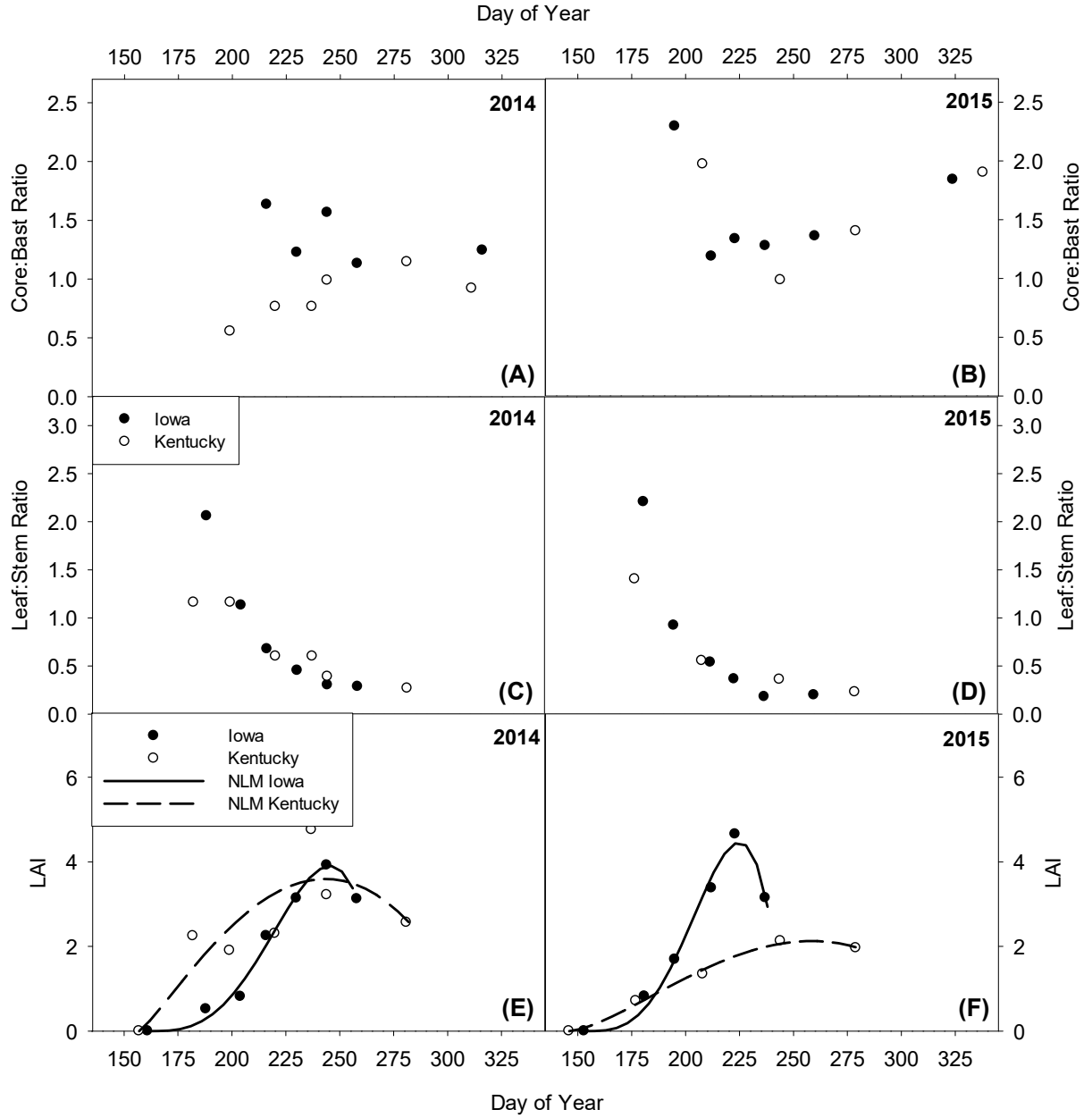




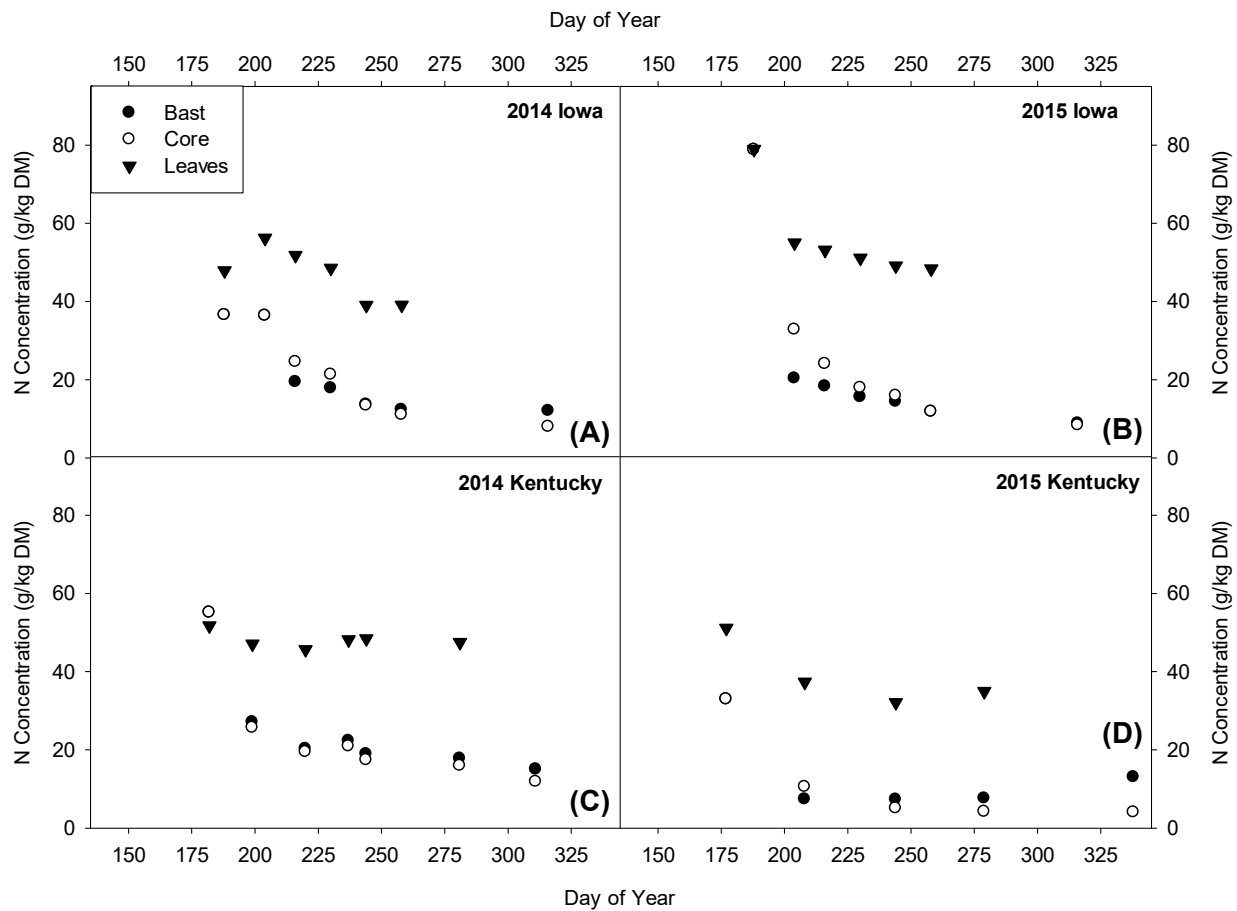
**Fig. 2.** Dry stem yield (2014 – A; 2015 – D), core:bast ratio (B), and stem diameter (C) of kenaf (mean  $\pm$  standard error; crop age 155, 154, 171, and 192 DAP for Iowa and Kentucky in 2014 and for Iowa and Kentucky in 2015, respectively) grown in Iowa and in Kentucky in 2014 and 2015, influenced by interactions with variety. Different letters on the top of the bars represent significant differences between treatments ( $P < 0.05$ ).



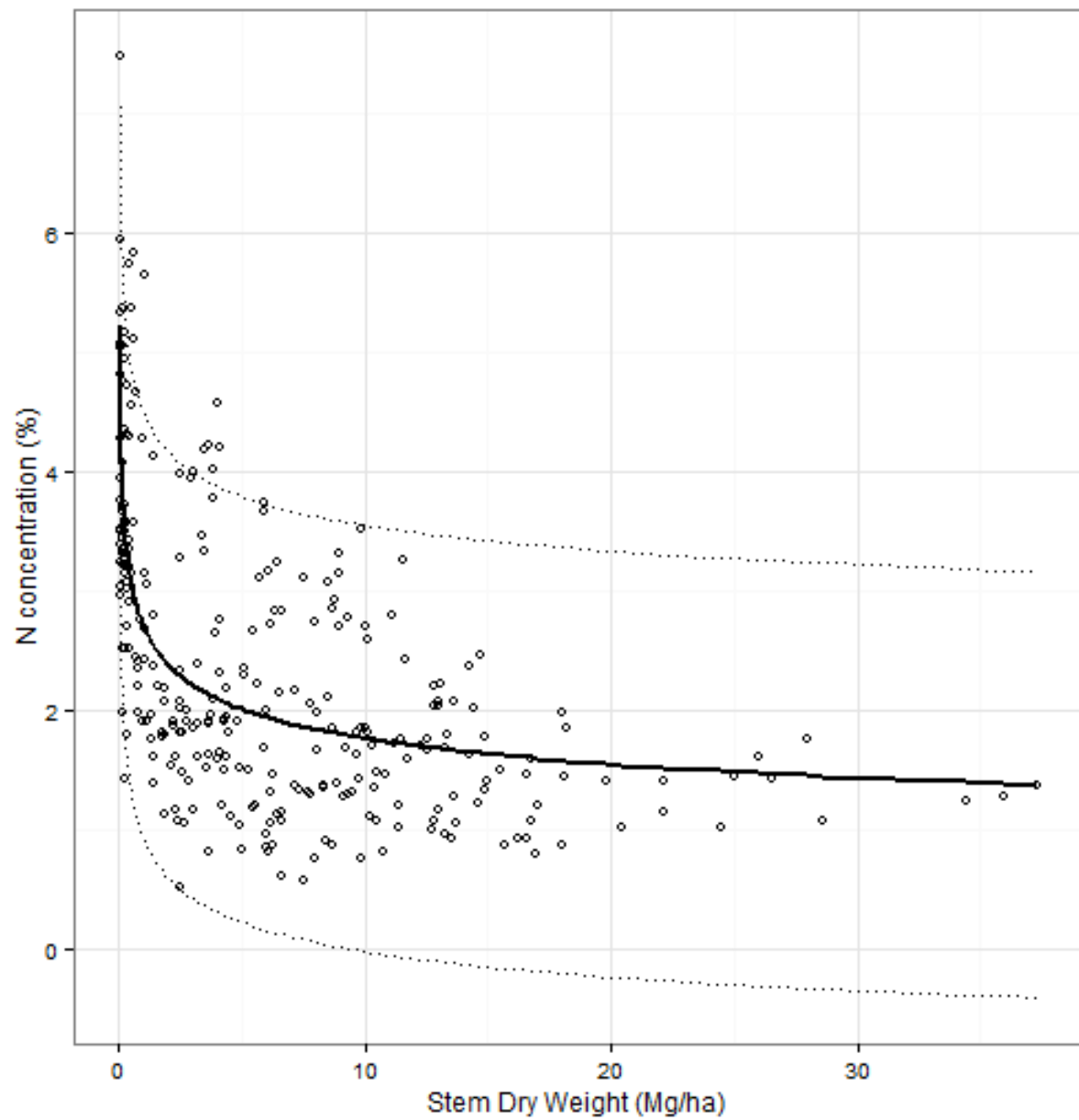
**Fig. 3.** Kenaf total aboveground dry biomass (2014 – A; 2015 – B), stem height (2014 – C; 2015 – D) and diameter (2014 – E; 2015 – F) grown in Iowa (●) and in Kentucky (○) in 2014 and 2015. “NLM” in the legend refers to “non-linear model”.



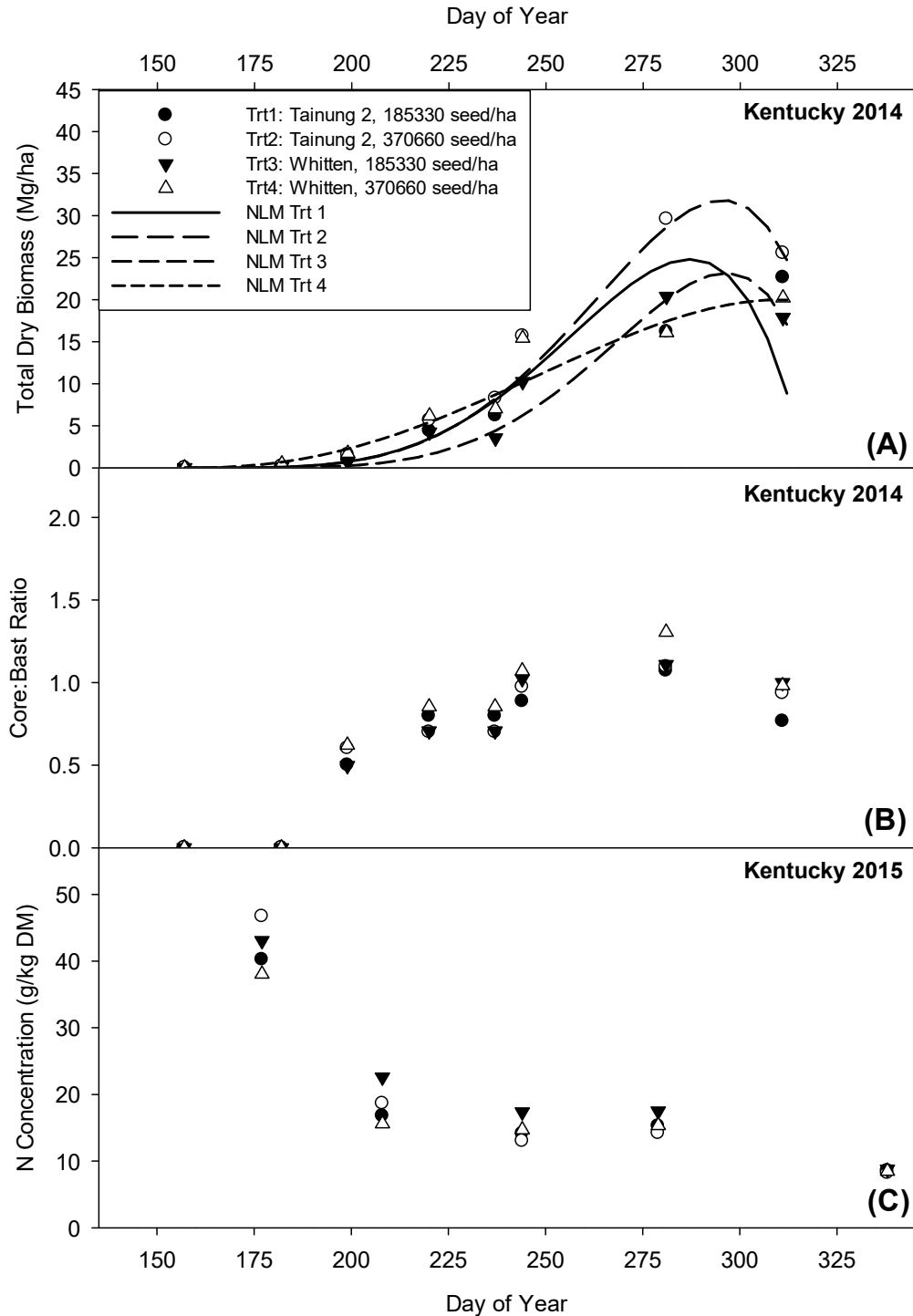
**Fig. 4.** Kenaf core:bast ratio (2014 – A; 2015 – B), leaf:stem ratio (2014 – C; 2015 – D) and leaf area index (LAI; 2014 – E; 2015 – F) grown in Iowa (●) and in Kentucky (○) in 2014 and 2015. “NLM” in the legend refers to “non-linear model”.



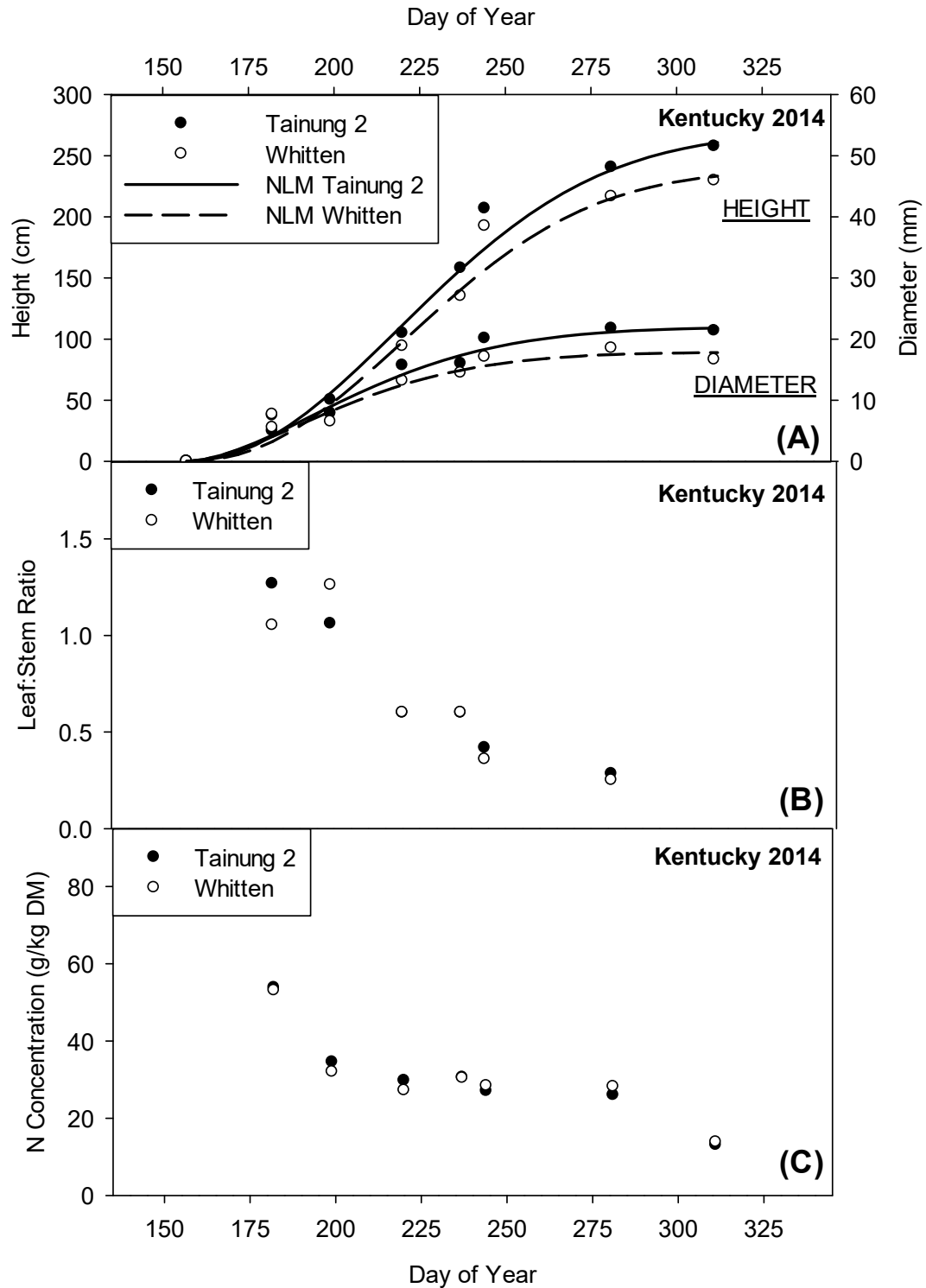
**Fig. 5.** Nitrogen concentration of bast, core, and leaves when grown in Iowa (2014 -A; 2015 -B) and in Kentucky (2014 -C; 2015 -D).



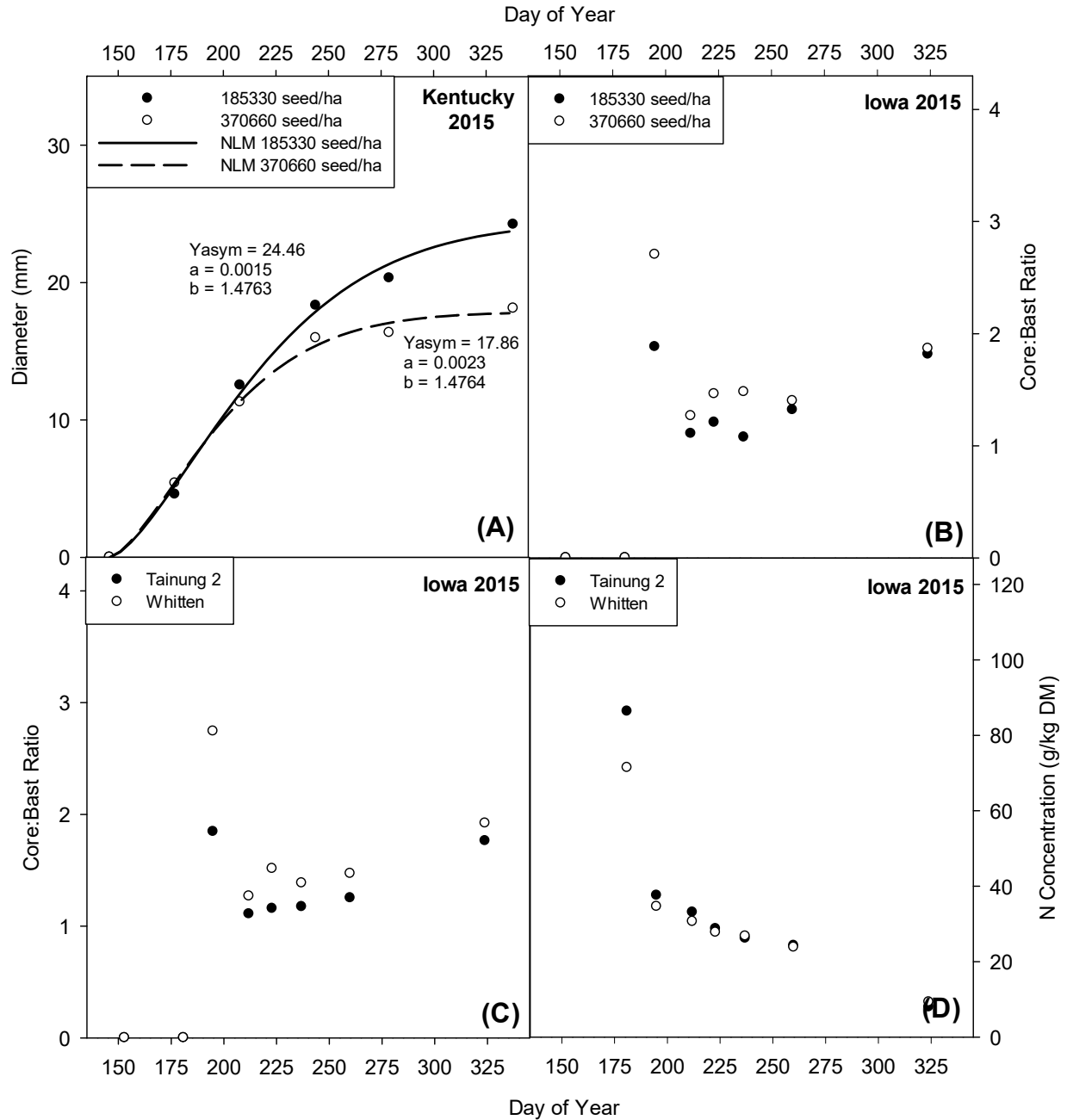
**Fig. 6.** Nitrogen dilution curve, showing N concentration and stem dry biomass of kenaf grown in Iowa and in Kentucky, in 2014 and in 2015. The bold line represents the mean and the dotted line indicated the 95% confidence interval.



**Fig. 7.** Harvest date, variety, and seed density effect on aboveground dry yield (A), core:bast ratio (B), and nitrogen concentration of kenaf grown in Kentucky in 2014 or 2015 (C). “Trt” and “NLM” in the legend respectively refer to “treatment” (combination of variety and seed density) and “non-linear model”.



**Fig. 8.** Varietal effect on kenaf height and diameter (A), leaf:stem ratio (B), and nitrogen concentration (C) of ‘Tainung 2’ and ‘Whitten’ grown in Kentucky in 2014. “NLM” in the legend refers to “non-linear model”.



**Fig. 9.** Seed density effect on stem diameter (A;  $Y_{asym}$ ,  $a$ , and  $b$  being the parameters for the Weibull function) and core:bast ratio (B) and varietal effect on core:bast ratio (C) and nitrogen concentration (D) of kenaf grown in Iowa and in Kentucky, in 2014 and in 2015. “NLM” in the legend refers to “non-linear model”.